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EDITORIAL

SPECIAL SECTION

Dynamics of rotating machinery

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1. PREFACE

It is well known that nature, specifically evolution never came up with a design similar to a rotating part turning around a shaft or an axle. It was human beings, most likely in the late Neolithic era, who invented the wheel to build better means of transportation. Accordingly, very basic rotating systems can be traced back to the times long before our era. Another application of this new design idea led to the invention of mills used for grinding grain, for instance. At that time, the dynamic of these early rotating systems was certainly not an issue. However, vehicles became faster and the source of power for mills changed from animals to waterpower or wind energy. Also, various other newly invented rotating machines became indispensable. With the increase of rotational speed and other parameters defining a rotating system, the design problems also increased. Overstressed materials, the wear of parts and occasionally strange and unexpected behavior of machines forced engineers to put more effort into the theoretical investigation of the design of rotating structures.

Consequently, at the time when rotating machinery became increasingly powerful, a new scientific field named “Rotor dynamics” was born. Famous scientists like Gustav de Laval, Arnold Sommerfeld, Henry Homan Jeffcott, August Föppl, and Aurel Stodola have been among those who established this specialized branch of applied mechanics at the turn of the 19th and the 20th century. Since then, more than 100 years have passed, and rotating machinery has become omnipresent in any kind of transportation, in nearly all industrial processes, in energy production and many other functions, and, last but not least, in our daily life.

In combustion engines, the linear motion of the piston is transformed into a rotation by the crankshaft, which delivers torque to the driving shaft. In an aircraft engine, a compressor draws and compresses air into a combustion section where fuel is added and ignited, and an exhaust nozzle accelerates the hot gases out of the back of the engine to generate thrust. In pipelines, pumps operate in stations along the pipeline to transport fluids from one end to the other. Paper machines, consisting of dozens of rotating cylinders produce a continuously moving wet mat of fiber that is then dried and squeezed in the machine to produce the final product paper. In a turbo generator, the shaft of a steam or gas turbine is connected to an electrical generator to generate electrical power. One could continue this list of rotating machinery nearly indefinitely. That is why it ends with the seemingly trivial example of a washing machine with an electric motor inside that drives a mostly unbalanced drum.

But apart from the obvious complexity of an aircraft engine or of a huge paper machine, what makes rotating systems so special that even a simple washing machine made it to the list above? One of the difficulties in the design, production, and operation of rotating machinery includes the inherent imperfections of such machines. To name one example, the unbalance of rotating parts can hardly be avoided in the manufacturing process. Therefore, especially high-speed rotors need to be carefully balanced before putting into operation. That is not a trivial task for large rotors or for lightweight rotors, which undergo elastic deformation at operational speed. And it can get even more complicated if the unbalance changes during operation. When running a washing machine, the load distribution changes during spinning, and this may cause some inconvenience. But when the blades of the fan of aircraft engines move slightly out of position because they must not be attached rigidly to the shaft, this may cause excessive vibrations and will require a shutdown of the engine.

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Unbalance is just one of the numerous imperfections that can hardly be avoided completely. Others are initial shaft bow, anisotropic shaft bending stiffness, and imperfections related to bearings and seals. Most of these other imperfections can also develop during operation and cause various vibration problems. Rubbing of the rotor shaft may generate a hot spot on the shaft, increase shaft bow, and lead to long-term spiral vibrations. A crack in the rotor shaft is a special case of an anisotropic shaft stiffness and may eventually lead to a total failure of the rotor system when the shaft breaks. Gyroscopic forces make natural frequencies speed-dependent and cause a splitting of the critical speeds, with vibration resonances that appear at unexpected rotor speeds.

As one can see from this discussion, rotor vibrations can be generated for various reasons. In most cases, these vibrations are considered to be deleterious and usually have negative effects of varying severity. Possible consequences are the destruction of machine parts, fatigue during the lifetime, and failed functions of the rotating machines. Avoiding vibrations is therefore of utmost importance, and in general, damping is one of the keys to vibration reduction. However, in rotor systems, one must distinguish carefully between external and internal damping forces. External damping can effectively reduce vibrations and is welcome in a rotor system. Internal damping, on the other hand, can lead to rotor instability, with potentially disastrous consequences. Sources of internal damping can be material damping of the rotor shaft or friction between the shaft and attachments. These damping sources can hardly be avoided and, in the worst case, even increase over time. A loss of dynamic stability of a rotor system must be avoided by any means. Therefore, mathematical models have been developed that are capable of representing such effects and phenomena and allow us to predict the dynamic behavior of a rotor system.

Most of the issues and examples discussed so far can be treated by linear system theory. This is important to know, since linear or linearized models are nowadays relatively easy to be treated numerically but do have a limited significance. However, complex bearing models, the mathematical representation of labyrinth seals, electromagnetic forces, impact forces, and others require a nonlinear description for better and more valid results. A much higher numerical effort is needed since the solution of the system equations must be found in the time-domain and not in the frequency domain as with linear systems.

In the last decades, many steps forward have been made in rotating machinery. New materials are in use and new bearing technologies have been introduced. Magnetic and foil bearings are particularly noteworthy. While the former ones are mostly active bearings that allow for completely new designs for the prize of a complex active control system, the latter ones are a passive and simple bearing type, which does use air as a lubricant. Both types have their advantages and disadvantages but are excellent solutions in specific applications. Also, the conventional oil bearings have been improved by adding oil-pressure systems to make them semi- or fully active bearings. Aside from new bearing technology apparently much progress has been made in specific rotating machinery, e.g. in automatic balancing.

Along with the progress in rotor system hardware, also the theoretical background, the software development for numerical investigations and experimental testing facilities advanced as well. Now, computer programs based on the finite element method do facilitate very detailed modelling of all rotor system components, including housing, support structure, and foundation with moderate effort. Nonlinearities can also be considered, but they increase the computational effort significantly. Linked to the advent of magnetic bearings, a unification of mechanical engineering, electrical engineering, and control systems could be observed. Nowadays, the term "Mechatronic System" is also appropriate for high-tech rotor systems.

Finally, a rather personal answer is given to the repeatedly asked question "Quo vadis rotor dynamics?". As recent years show, there is always the potential for improvements and even for new ideas in bearing technology. In combination with magnetic bearings, control systems can significantly improve the dynamics of rotor systems. So, maybe in the future separate active components will be combined with bearings or damping devices for more flexibility in the dynamic properties of high-performance rotating machinery.

As computer hardware, numerical and experimental methods, and related software are undergoing permanent performance increases, one can expect that fluid-structure studies for turbines and pumps will become easier and less time-consuming to conduct. This should enable design optimization with respect to efficiency and vibration minimization at the same time.

Improved rotor dynamic models will not only help to optimize the design process but will be part of a rotating machine as a digital twin over the lifetime to support monitoring and diagnosis procedures and to find the best solutions for vibration control in problem cases.

Electric drives will definitely become even more popular in the coming decades and will gradually replace combustion engines. As electrical motors will also undergo the typical optimization process of decreasing weight and costs but increasing performance at the same time, rotor dynamics will become more important also for this kind of rotors. The same is more or less true for wind turbines. Offshore wind turbine parks, e.g. will operate in a "hostile environment" for a rotodynamic system and we can expect that this situation will demand further advances in the design and the numerical analysis of such systems.

Aside from this personal view of the authors of this preface, the 13 papers in this volume also show in which direction top researchers are currently working and what to expect for the future of rotor dynamics.

2. INTRODUCTION TO THE PAPERS

The issues dealt with in the 13 articles of this Special Section fully reflect the current research trends in the field of rotating machinery dynamics. As emphasized in the introductory paper [1], despite many decades of development of the field of knowledge called "rotor dynamics", many problems still need to be resolved. This is because the rotating machines, both with low and high output power, have a very complex structure. The author of this article highlights the problems in the form of some questions to which we still do not have precise answers. The most essential questions are: How can we build a coherent dynamic model of a turbomachine whose certain subsystems have non-linear characteristics? How can we consider the so-called "prehistory" in our analysis, namely, the relationship between future dynamic states and previous ones? Is heuristic modelling the future of rotor dynamics? What phenomena may occur when the stability limit of the system is exceeded? The attempt to find answers to the above questions constitutes the subject of this thought-provoking article.

Several articles still discuss problems of various types of rotor shaft bearing supports. In paper [2] there is investigated a thrust bearing with an additional separating disk between the journal collar and housing. This kind of thrust bearing and its implementation are addressed in a transient rotor dynamic simulation by solving the Reynolds partial differential equations online by means of direct integration. Here, special attention is focused on the coupling between the different fluid films on both sides of the separating disk.

A new design of a hydrodynamic bearing lubricated with magnetically sensitive composite fluid is presented in paper [3]. The magnetic flux generated in the electric coil passes through the bearing housing and the layer of lubricant, and then it returns back to the coil core. An action of the magnetic field on the lubricant affects the fluid apparent viscosity and thus the position of the rotor journal in the bearing gap. The mathematical model of such bearing is based on the solution of the Reynolds equation that has been adapted in the case of lubricants exhibiting the yielding shear stress. The results of simulations confirmed that changes of the magnetic induction result in changes in the bearing load capacity and thus in keeping the rotor journal eccentricity in the required range.

The issue of supporting rotors with actively controlled magnetic bearings is still relevant and prospective. Paper [4] deals with research on the subject of magnetic bearing control systems for an aviation jet engine. These control systems are based on standard and advanced algorithms. In this article, theoretical and experimental characteristics of the control systems were obtained through the model algorithmic predictive control and the well-known proportional-derivative control, operational effectiveness, and accuracy of which have been mutually compared.

In addition to the magnetic levitation applied for actively controlled rotors, piezoelectric active suspensions become now very promising. Thus, in paper [5] a gyroscopic rotor exposed to unbalance is controlled with an active piezoelectric bearing. For this purpose, proper models are required to design a proper controller. Due to the lack of related publications utilizing piezoelectric bearings and obtaining such models, this paper reveals a method to receive a modal model of a gyroscopic rotor system with an active piezoelectric bearing. Properties of the retrieved model are then incorporated into the design of an originally model-free control approach for the elimination of unbalanced vibration, which consists of simple feedback control and adaptive feedforward control.

The touchdown bearings constitute a separate class of supports when applied to fast-spinning rotors suspended by touchless bearings, e.g., magnetic or gas bearings. Various materials are used in the construction of the touchdown bearings to ensure their required load-bearing capacity and tribological durability. Therefore, in paper [6] the influence of elastomer rings around the outer rings in a touchdown bearing through numerical simulations is investigated. For this purpose, there are presented structural models taking into consideration the properties of elastomers in order to calculate the bearing contact forces. Based on the requirements for a touchdown bearing in a flywheel application, three different elastomers, i.e. FKM, VMQ, and EPDM, are selected for the investigations. The results of simulations show that stiffness and material properties strongly influence the maximum transmitted force. The best results have been obtained when using the material FKM, which enables a reduction of the transmitted force amplitude in a wide bearing stiffness range.

A suppression of lateral vibrations of the rotor-shaft systems utilizing their appropriate support is still an important challenge for researchers and machine operators. For this purpose, squeeze film dampers, which are of similar geometry as hydrodynamic bearings, can be successfully used. In article [7] the Reynolds equation describing the lubrication model is applied to predict the dynamic behavior of such support. But under certain operating conditions squeeze film dampers can be affected by significant fluid inertia effects, which are usually neglected when using the standard Reynolds analysis. Thus, in this paper, an algorithm for the prediction of these effects influencing the pressure build-up inside a finite-length squeeze film damper is presented. The algorithm developed for this purpose is capable to determine the pressure field, and thereby the damping force, inside a squeeze film damper for arbitrary operating points in a time-efficient manner. Therefore, it is suitable for simulating transient rotor-shaft lateral vibrations without the need to map bearing force coefficients, which are usually limited to circular centralized orbits.

Balancing and the identification of unbalance are still open questions in the rotating machinery dynamics. In order to improve computational tools necessary to solve these problems, more and more advanced modelling methods of rotor-shaft systems are being currently developed. For this purpose, in articles [8, 9] the quasi-analytical Numerical Assembly Technique is presented for balancing linear elastic rotor-bearing systems with stepped shafts and mass unbalances arbitrarily distributed in space. This method improves existing balancing techniques by combining the advantages of modal balancing with fast calculation using an efficient numerical method. The rotating stepped shaft is modelled according to the Rayleigh beam theory, including rotatory inertia and gyroscopic effects. Rigid disks can be attached to the rotor, and the bearings are represented by linear translational/rotational springs/dampers, including cross-coupling effects. The Numerical Assembly Technique is used to calculate steady-state harmonic responses, eigenvalues, and mode shapes of the rotor. The calculated displacements are compared with the measured displacements of the rotor-bearing system to determine the generalized unbalance for each eigenvalue. The generalized unbalances are then modified in order to calculate modal orthogonal correction masses. In this way, a rotor-bearing system is balanced using a single measurement of the displacement at one position on the rotor for every critical speed.

Also, the study in [10] proposes a novel, model-based method for a direct estimation of residual unbalances in a single plane and two planes after initial grade balancing of large flexible rotors operating at arbitrary service and critical speeds. This method uses results of vibration measurements from two planes in any single direction, combined with computational results obtained using a FE rotor model, in order to determine the residual unbalance in one and two planes through the inverse problem solution. This method can be practically applied to determine initial and residual unbalances after the balancing process, and further, it can be used for condition-based monitoring of the unbalance state of the rotor.

In addition to unbalance, detection, and identification of other types of imperfections common in the rotor-shaft systems have become the subject of intense research over the last 2–3 decades. According to this trend, in [11] for the rotating machines with overhung rotors, there is investigated an influence of dynamic and static unbalance of a heavy impeller, parallel and angular misalignments of shafts as well as inner anisotropy of rigid couplings on system dynamic responses. The considerations are carried out through an advanced hybrid structural model of the machine rotor-shaft system, which consists of continuous beam finite elements and discrete oscillators. The main goal of this research is to assess the sensitivity of the above-mentioned imperfections on excitation severity of rotor-shaft linear and parametric lateral vibrations and motion stability of the rotor machine. To achieve this target, the harmonic balance method, as well as the interval approach for system uncertain parameters, were employed.

Fluid-flow problems have always been and are an integral part of the dynamics of rotating machinery. In this Special Section, an analysis of subsonic stall flutter in turbine blade cascade is conducted in [12] using a medium-fidelity reduced-order aeroelastic numerical model. This model uses the field meshfree approach and is built through the hybrid boundary element method. The medium-fidelity flow solver is developed based on the principle of viscous-inviscid two-way weak-coupling approach. The hybrid flow solver is employed to model separated flow and stall flutter in the 3D blade cascade at subsonic speeds. The aerodynamic damping coefficient with the phase angle related to the inter-blade in the traveling wave mode is estimated along with other parameters used next to analyze the cascade flutter resistance regime. The estimated results are then validated against experimental measurements as well as based on the Navier-Stokes high fidelity computational fluid dynamics model.

The so-called miscellaneous problems and case studies are an inseparable subject of considerations in many publications in the field of rotating machinery dynamics. As a typical example, state-of-the-art analyses for the rotor dynamic assessment of pumps and specific requirements for the simulation tools are described in [13]. These examples are the horizontal multistage pump with two fluid film bearings in atmospheric pressure, the horizontal submerged multistage pump with many bearings, and the submerged vertical single-stage pump with water-lubricated bearings. The stability of these pumps is assessed through the Campbell diagrams considering linear seal and bearing properties. The results of all these examples have a practical background in engineering practice, although in the authors' opinion they do not always exactly correspond to real cases.

The above review of 13 papers published in this Special Section shows a multitude of unsolved or not fully resolved issues related to the dynamics of rotating machinery. However, one should be aware that the number of these problems is even greater, and with the widespread technological development, it may constantly increase. This situation poses a constant challenge for researchers and engineers to commit their efforts to the further development of this extremely important subfield of machine dynamics, which is the dynamics of rotating machinery.

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Horst Ecker was born and raised in Vienna, Austria. He joined Vienna University of Technology and enrolled in Mechanical Engineering. His major was transportation and traffic engineering, but he was also very interested in the dynamics of machines. He stayed with TU-Vienna for his PhD study and completed his thesis on a model for non-steady-state tyre mechanics. To his great delight, he was offered a post-doc position at TU-Vienna by Professor Helmut Springer and began to work on non-linear phenomena of magnetic bearing. The Max Cade fellowship allowed him to stay for a year at Duke University in Durham, NC to continue his research work. After returning from the USA, he met Ales Tondl at an IFToMM rotor dynamics conference and this was the start of long-lasting cooperation on rotor dynamics and parametrically excited systems. The latter topic also led him to his habilitation on vibration suppression in time-periodic systems.

This work earned him the degree of a docent and he was promoted to Associate Professor at TU-Vienna. In the following, he was again invited to Duke University to teach courses on Vehicle Dynamics. Upon the retirement of Professor Helmut Springer in 2006, he took over the position of a professor for Technical Dynamics until September 2021. Since then, he has been retired, but still associated with TU-Vienna and continues teaching and doing research work on various kinds of dynamical systems.

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Rainer Nordmann studied mechanical engineering at TH Darmstadt and then undertook PhD research in rotor dynamics at the same university. He was appointed Professor of machine dynamics at the University of Kaiserslautern in 1980, and was teaching machine dynamics and control. In 1996 he became Professor of mechatronics in mechanical engineering at TU Darmstadt. His research activities at TU Darmstadt were concentrated on the development of mechatronic systems with applications to rotating machinery, machine tools, and automotive systems. He was involved in several research projects and supervised more than 100 PhD students. The methods and results of his research were published in several papers in international journals and were also presented at national and international conferences. Rainer Nordmann is co-author of two Springer books: "Rotordynamik" and "Magnetic Bearings".

After his retirement in 2009, Rainer Nordmann worked from 2009 to 2012 as manager for rotor dynamics in the International R&D Center of Alstom Power in Baden (Switzerland). From 2009 until 2016 he was Chairman of the ISO Working Group "Rotor Dynamics and Vibrations of Machines" and from 2006 until 2011 Chairman of the IFToMM Technical Committee Rotor Dynamics. Today he is working as a consultant for the Fraunhofer Institute for Structural Durability and System Reliability LBF in the area of mechatronics.

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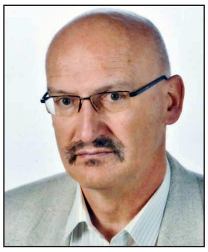

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In 1993–1994 he was a visiting researcher at the Institute of Mechanics of the University of Hannover in the framework of the joint German-Polish Research Project realization. In the years 1994–1996, he completed a research internship as a scholarship holder of the Alexander von Humboldt Foundation at the University of Technology Hamburg-Harburg (TUH-H) and at the University of Stuttgart. As part of his teaching activities in 2006–2012, he worked as a professor at the Department of Mechatronics of the Warsaw University of Technology. Since 2008 he has held a professor position in the Institute of Fundamental Technological Research, since 2012 he has been the Head of the Doctoral Studies of IPPT PAN, and since 2019 the Head of the Doctoral School of IPPT PAN. In 2019 he obtained the academic title of full professor of engineering and technical sciences.